AFRL-OSR-VA-TR-2014-0067

Real-time Location of Targets in Cluttered Environments

John Steinhoff
WAVE CPC INC

03/13/2014
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 31/12/2013	**2. REPORT TYPE** FINAL REPORT	**3. DATES COVERED** *(From - To)* 03/01/2013 - 11/30/2013

4. TITLE AND SUBTITLE
REAL TIME LOCATION OF TARGETS IN CLUTTERED ENVIRONMENTS

5a. CONTRACT NUMBER
FA9550-13-C-0020

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
JOHN STEINHOFF, SUBHASHINI CHITTA

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
WAVE CPC, INC
19 BROOK HOLLOW LANE,
PO BOX 962, WINDHAM, NY 12496-0962

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF OFFICE OF SCIENTIFIC RESEARCH
875 NORTH RANDOLPH STREET
ARLINGTON, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
NO RESTRICTIONS

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The consequences of windmill farms to radar systems presents a difficult challenge, especially when windmill farms are located near Air Force bases. Unfortunately, the requirements for locating the bases and farms results in conflicts, when the bases in flat areas away from populated areas and wind farms on higher ground surrounding them (as is often the case). The problem that we are addressing concerns any low flying aircraft approaching a base over such a wind farm. The current STTR project involves developing a method, based on using modern radar, enhanced
with the new technique, Wave Confinement (WC), to accurately locate low flying aircraft approaching areas such as Air Force bases. Conventional schemes involve estimating the target location based on assumptions of the radar propagation path that often neglect important effects, when integral equation methods are used. These effects include index of refraction variations,

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** JOHN STEINHOFF
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)* 931-455-4370

FINAL REPORT – FA9550-13-C-0020

REAL-TIME LOCATION OF TARGETS IN CLUTTERED ENVIRONMENTS

Primary Contractor: John Steinhoff, Subhashini Chitta and Andrew Wilson, Wave CPC, Inc.

Subcontractor: Eric Michielssen, University of Michigan.

REPORTING PERIOD: MARCH 1ST, 2013 TO NOVEMBER 30TH, 2013.

CONTENTS

ACCOMPLISHMENTS

1. A 3D code is developed for propagating the small scale return signals to the far field.
2. Validated using analytical signals.
3. Inner field scattering from a wind turbine and aircraft is computed
4. An interface is developed to couple the above far field code with inner field code.
5. Far field scattering from a single wind turbine is done by coupling the far field code to inner field data.
6. Far field scattering from multiple wind turbines with and without aircraft is computed
7. Multiple return signals due to ground reflection are also computed.

INTRODUCTION

The current STTR project involves developing a method, based on using modern radar, enhanced with the new technique, Wave Confinement (WC), to accurately locate low flying aircraft approaching areas such as Air Force bases. Conventional schemes involve estimating the target location based on assumptions of the radar propagation path that often neglect important effects, when integral equation methods are used. These effects include index of refraction variations, terrain reflections and "clutter" from nearby objects. Currently, the only alternative method—"Ray Tracing"—can take some of these effects into account, but it involves an incoherent collection of "rays", from which it is difficult to extract information. Ray tracing computations can even become chaotic near caustics, or neglect caustics altogether. Details of the basic method are included in Ref[1] and some new developments are briefly discussed in this report.

The consequences of windmill farms to radar systems presents a difficult challenge, especially when windmill farms are located near Air Force bases. Unfortunately, the requirements for locating the bases and farms results in conflicts, when the bases in flat areas away from populated areas and wind farms on higher ground surrounding them (as is often the case). The problem that we are addressing concerns any low flying aircraft approaching a base over such a wind farm.

Characterization of radar returns from a windmill farm would be feasible if the individual windmills were placed far apart, or were all in air flowing at the same speed and direction. However, the farms often have several hundred turbines spaced only a few diameters apart, each of which is exposed to varying winds because they are at different locations in a complex topography. The scattered signals will undergo refraction, multiple reflections and diffraction. In the present project, diffraction is not addressed although some work has been done[2].

The final outcome achieved at the end of the phase I contract is the demonstration of the capability to compute a return signal from a multiple wind turbines, when an aircraft is flying over as shown in Figure 1. This capability can be used in future to a) determine the location of any aircraft present and b) develop a tool to model the atmosphere, which plays a major role in accurate detection.

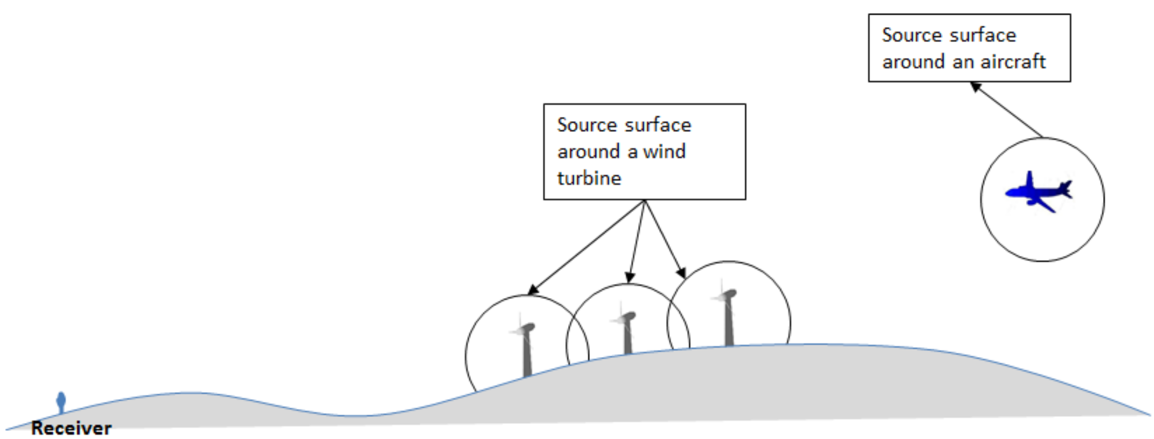

Figure 1: Problem to be solved during this project

[1] Steinhoff, J. and Chitta, S., "Solution of the scalar wave equation over very long distances using nonlinear solitary waves: Relation to finite difference methods," *Journal of Computational Physics*, Vol. 231, No. 19, 2012, pp. 6306–6322.

[2] Steinhoff, J. and Chitta, S., "Long distance wave computation using nonlinear solitary waves," *Journal of Computational and Applied Mathematics*, Vol. 234, No. 6, 2010, pp. 1826–1833.

There are two spatial scales that must be resolved for the above wave propagation problems:

a Large Scale – On the scale where variations in the medium and scattering surfaces are O(L), the wave packets appear as propagating and reflecting codimension one surfaces. (2-D for 3D solutions for thickness, d<<L.) These surfaces propagate along the local normals (for isotropic media), refract and undergo reflection. (Only specular will be considered here.) Thus, at this scale, the problem involves only surfaces either stationary (reflecting) or propagating (waves) along local normals.

b Small Scale – The small scale wave packets, just like the above surfaces, propagate along "rays" as in Hamilton Jacobi methods. The "waveform" that they carry is invariant in time[3] except for dissipation and geometric changes in intensity. The latter can be included as multipliers of the wave forms, so that only initial wave forms need to be specified for each ray.

METHODOLOGY

In this report, we describe a new, simple, computationally efficient wave simulation method that overcomes most of the problems of conventional methods for long distance propagation in inhomogeneous media, including multiple reflections. In its initial form, it involves the scalar wave equation with non-dispersive and non-diffusive media, but these limitations can be removed in future versions with perturbation terms. This new method is termed the "Generalized Eikonal Method" (GEM).

The solution at any distant receiver ("distant" meaning "many wavelengths away") is assumed to be represented by smooth variables (away from caustics): attenuation factor (A_k), propagation vector (S_k), arrival time (τ). It is assumed that the wave equation is accurately computed (with conventional methods) in a small region surrounding the source/target, with dimensions comparable to the wavelength of interest (λ). In general, because of the reflections and refractions in realistic media, the wave paths, or Eikonal phase will be multi-valued in some regions of space, which represent multiple passes of the wave front. Then, at each grid node, an array of phase is stored, one for each wave front passage. This is easily accomplished using a counter, which serves as an array index (k). For each k, or "trajectory", the recently developed method – "Wave Confinement" – (WC), is used to solve a modified wave equation. This method generated values of ψ_k at grids nodes when equation (2) is discretized.

$$\partial_t^2 \psi = c^2 \partial_x^2 \psi + E \tag{1}$$

where E s a combination of positive and negative (stable) dissipation. The purpose of this modification is to generate short, coherent Solitary Waves which represent wave fronts. When

[3] Steinhoff, J., "A New Eulerian Method for the Computation of Propagating Short Acoustics and Electromagnetic Pulses," Journal of Computational Physics, Vol. 157, 2000

equation (1) is discretized, the solitary waves persist, remaining concentrated over only 2-3 grid cells, unlike conventional numerical schemes, where the waves dissipate. In this way, it is computationally feasible to solve for wave propagation over a large region, containing many waves.

The problem described above is solved in 4 steps: a) Near Field generation on a source surface surrounding known emitters or targets such as windmills and aircraft. b) Large scale far field propagation, which computes accurate wave front propagation. These wave fronts are much larger compared to the physical waves and act like basis functions, whose centroids propagate as those of small scale physical waves. The Wave Confinement method accurately propagates these wave fronts with no numerical dissipation as nonlinear solitary waves, which retain their shape and size indefinitely. c) Computation of small scale return signals by applying the arrival time, attenuation factor and propagation vector computed using b) to the detailed signal computed using a). The small scale details are propagated to the far field in this step by tracing back the point of origin using the near field information saved on a source surface around the scattering objects.

NEAR FIELD SCATTERING

A new parallel fast Fourier transform and fast multipole method (FFT-FMM) -accelerated surface integral equation solver has been developed which is capable of analyzing scattering from wind turbines in the high-frequency regime. The novelty of the solver lies in its parallelization scheme as well as the use of a singular value decomposition scheme for compressing near-field interactions. Here, the solver is applied to the analysis of scattering from a wind turbine at 300 MHz; the analysis required 10,114,062 unknowns. The time history of the scattered signal is computed on a source surface surrounding the near field of a scattering object, which will later be used to reconstruct the signal at any far field point. Note: In the current project, the time history of the electric field intensity envelope is used for simplicity because the main objective of the report is to show the demonstration of a coupled inner field near the wind mill and the WC based far field method.

FAR FIELD PROPAGATION

Since the medium is non-dispersive and non-dissipative, if we trace a particular ray (in our case, a short segment of a wave front), from the source to the receiver (including refractions and reflections), the wave *form* will be the same as a function of time, t, on the emitting surface, as well as at the receiver: Only the time will be translated (by the travel time) and the amplitude will be multiplied by a factor that depends on the cross sectional area of the ray at the two locations.

Two quantities must now be determined: Translation time, and amplitude ratio. A simple way to determine the direction vector of the ray that will reach the receiver (and hence the initial amplitude at the source), the travel time and amplitude ratio of the ray, is to start from the *receiver* and propagate *backward in time,* taking account of reflections and refraction. We employ the time reversal invariance property of the wave equation to equate this result to that from a direct, forward time computation. The result will be a wave at the source which is almost a plane wave, with a smoothly varying direction vector, arrival time, and amplitude. These quantities will be computed on the coarse "outer" grid, which spans the distance between the source and the receiver.

In general, because of the reflections and refractions in realistic media, the wave paths, or Eikonal phase will be multi-valued in some regions of space, which represent multiple passes of the wave front. For this reason a straightforward finite difference iteration solution scheme of the governing Hamiltonian - Jacobi equation is not feasible. To accommodate these features, we take propagation time as an extra variable and, using local characteristics, solve for the wave fronts as they propagate through these regions, employing the FDTD scalar wave equation, including these multiple paths, if necessary. The wave fronts that we describe essentially represent "bundles" of particle trajectories. The computation of multiple phase regions was previously reported by the PI in a closely related study of short acoustic wave propagation[1].

We first define an artificial isotropic wave, ψ, which is emitted at the receiver location. This GF wave is numerically confined with our WC method and projected backward in time. Because of WC, the wave remains thin (2-3 grid cells) throughout the propagation to the distant source region, ensuring a close representation of the wave front. There, for long distance propagation, the GF wave is approximately a plane wave. We assume that the total number of grid cells in each direction is limited to few hundred for a feasible computation. For propagation distances of ~ 10 km, the width of the captured wave, which is ~ 2 grid cells (with WC), can still be 2-3 orders of magnitude larger than the desired resolution limit of the thinnest physical signals. This, of course, precludes a direct numerical solution of the wave equation, but does not preclude a WC based numerical Greens function that retains the ability to treat refraction and reflections. WC can accurately propagate thin waves since they follow the same trajectories as the much longer resolved waves.

Large Scale

To summarize, the Greens function computed using WC involves computation of a "GF" wave "emitted" from the receiver as $\psi\left(x,\tau^{rec}\right)$ and "reverse propagated" to the physical source. For an receiver with an isotropic receptivity, a unit initial amplitude is taken. As stated, near the source, the wave amplitude, ψ, can be multi-valued due to multiple paths from refraction and reflection. We index the values according to the time of passage in the (physical) source region. Since ψ is confined to only ~2-3 grid cells, direct partial derivatives approximations cannot be used to compute derivatives and propagation directions, as in conventional numerical schemes. Instead, expectation values, which involve time integrals as the wave passes over each node (labeled (*i, j*))

$$\langle\psi\rangle_{i,j} = \int \psi_{i,j}\,dt$$

$$\tau_{i,j}^{rec} = \langle\tau\rangle_{i,j} = \frac{\int t\psi_{i,j}\,dt}{\langle\psi\rangle_{i,j}}$$

$$\vec{k}_{i,j}^{rec} = \nabla\tau_{i,j}$$

where t is the travel time of the reversed wave from the receiver to the (*i, j*) node. An amplitude ratio ($A_{i,j}^{rec}$), which is the ratio of the observed amplitude ($\langle \psi \rangle_{i,j}$) to the emitted amplitude is also computed. These are accurately defined due to the conservation properties of WC, and are expected to be smoothly varying in the source region. The "receiver" times $\tau_{i,j}^{rec}$ will also be smooth.

Small Scale

Now, we project out the waves that will intersect the receiver, $\vec{k}_{l.m}^{source} = -\vec{k}_{l.m}^{rec}$ and at desired receiver times, $t_{i,j}^{rec} = \tau_{l,m}^{rec} + \tau_{l,m}^{source}$. At any far field point, the physical signal is computed as

$$E\left(\overline{x}, t^{rec}\right) = A\left(\overline{x}_{source}, t^{rec}\right) * E\left(\overline{x}_{source}, t^{rec}\right)$$

Validation

For validation, an initial distribution defined by $E = \frac{A}{r} exp\left(-\beta r^2\right)$ on the source surface around an object is propagated to the far field receiver. The integral variables required to reconstruct the physical signal are computed by propagating an isotropic wave from the receiver. This computation involves a linearly varying index of refraction and could not be done using a Kirchhoff method, which requires a closed form Greens function. In Figure 2, the analytical signal is compared to the signal computed using WC and they match quite well.

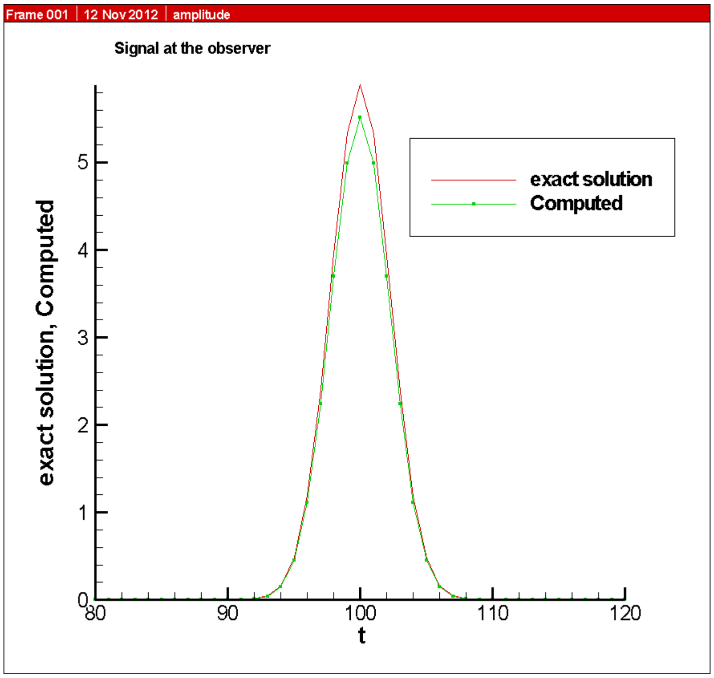

Figure 2: The waveform at the receiver location for an initial distribution of $\phi = \frac{A}{r} exp\left(-\beta r^2\right)$

DEMONSTRATION

RETURN SIGNAL COMPUTATION FROM A SINGLE WIND TURBINE

The new method described in the above section is used to compute the return single from a single wind turbine as shown in Figure 3.

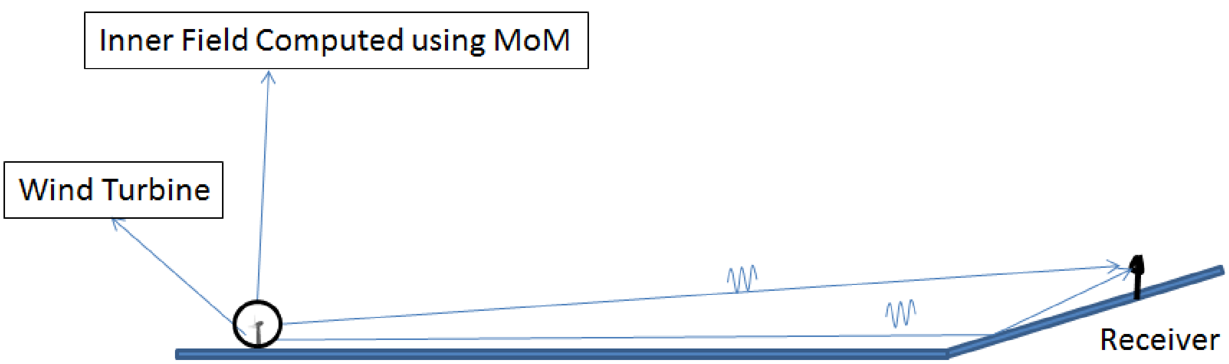

Figure 3: Problem Setup

Time history of the scattered signal computed in the near field using MoM described in the proposal is saved on a source surface around wind turbine. The radius of the sphere is 3R. In the present case, the time history of Electric field intensity is used for simplicity because the main objective of the report is show the demonstration of a coupled inner field and far field method.

Below are the details of the inner field computation (supplied by Eric Michielssen):

The antennas are located few kilometers away from the wind farms and so the EM wave that reaches any wind turbine is planar. So, the wind turbine is illuminated by a plane-wave (propagating along y direction). E-field with unit magnitude is polarized along z direction. The blades of wind turbine lie on yz plane and the ground is assumed to be located on xy plane. The near field points are selected on a sphere with the radius of 125m (3 times blade's length). Center of sphere is positioned at (0, 0, 0). 50 samples are selected along theta direction and 100 samples are selected along phi direction. Intervals for theta and phi angles are assigned as [0 180], [-90 90], (in degrees), respectively. So totally, there exist 5000 near field points on half-sphere. The period of blade rotation is set to 3 seconds. The envelopes of sums of squares of E-field components at near field points are computed at 1441 points from t=0 to t=3 seconds and stored on the source surface. In Figure 4, a snapshot of the Electric field intensity is shown on a sphere of radius 3 rotor radii with wind turbine at the center.

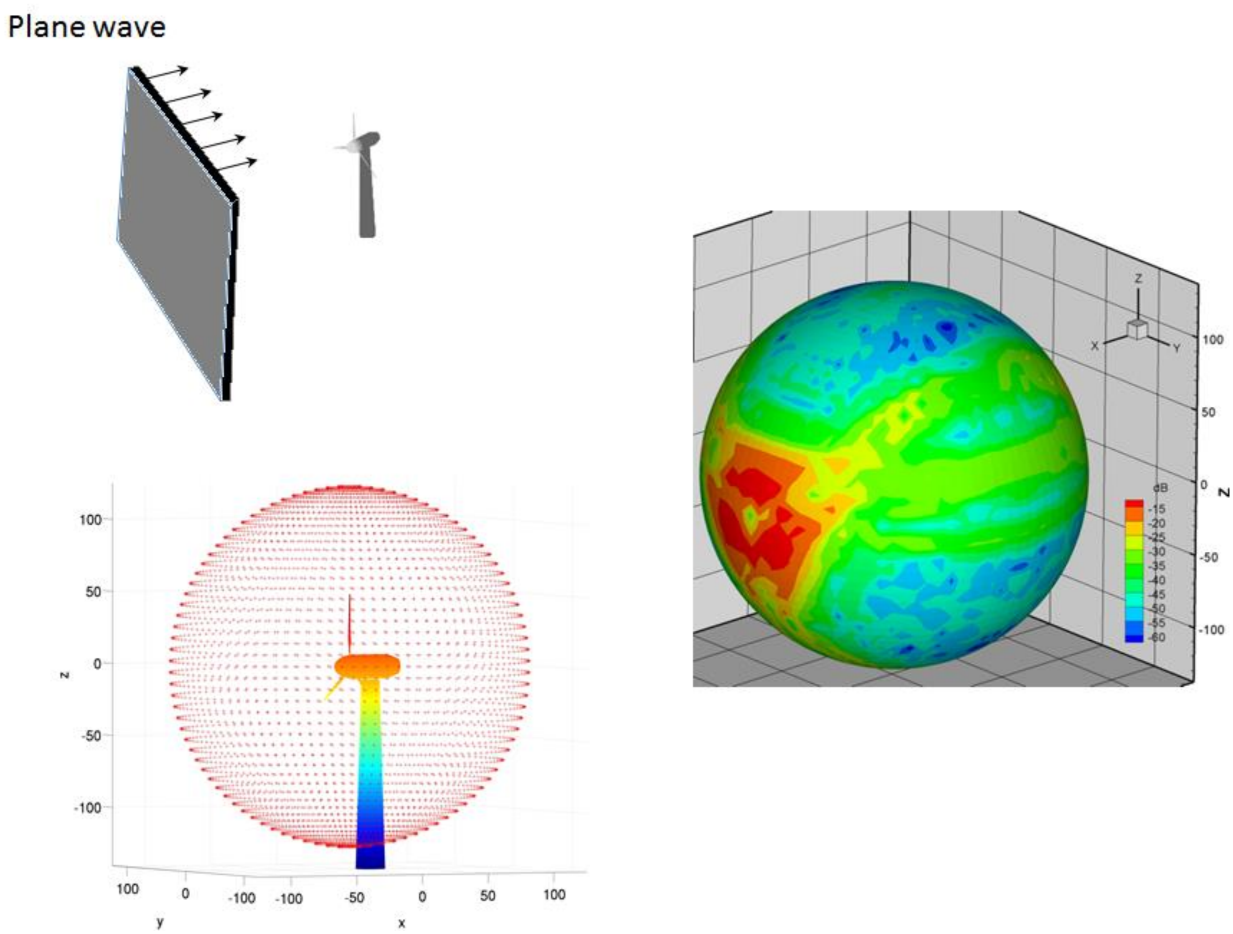

Figure 4: Near field computation

Nonlinear solitary wave propagation, taking into account reflection and refraction, can provide information about the region on the inner field that accounts to the signal at the receiver, which will then be used to compute the signal. For multiple arrivals, point of origin and return signals corresponding to each arrival are computed. For the above case, the return signal at a receiver placed ~700m away. The computed first arrival (incident) and second arrival (reflected) signals are plotted against the exact signals in Figure 5 and Figure 6 respectively and they seem to match well.

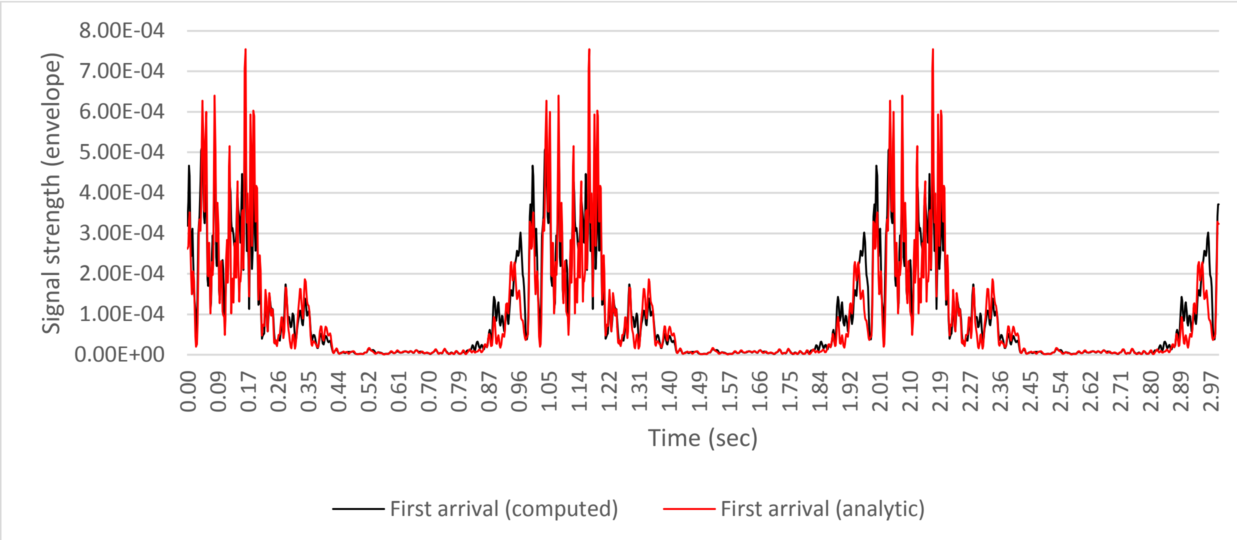

Figure 5: First Arrival for One Windmillat ~700m distance

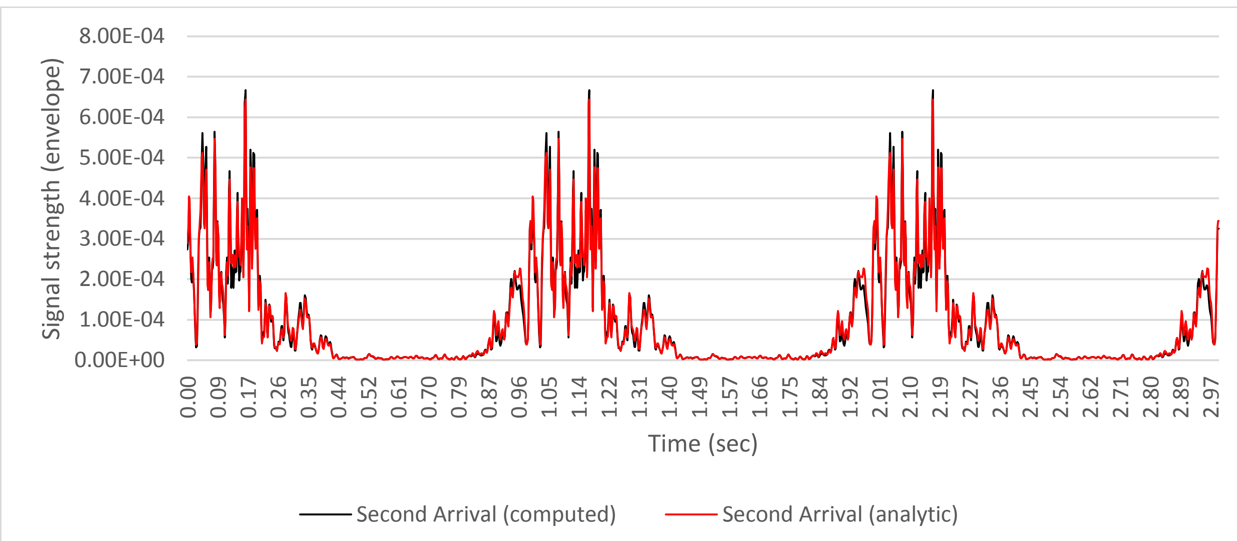

Figure 6: Second Arrival for One Windmill

Return Signal From Multiple Wind Turbines With and Without Aircraft

Another demonstration to compute the return signal from a notional wind farm with and without aircraft is described below. The locations of receiver, wind farm and aircraft are shown in Figure 7 and a schematic of the problem description is shown in Figure 8.

Object	X (meters)	Y (meters)	Z (meters)	Turbine rotation (degrees)	Velocity of airplane (m/s)
Receiver location	15	15	5		
Turbine 1	100	400	120	0	
Turbine 2	300	400	120	30	
Turbine 3	500	400	120	60	
Turbine 4	700	400	120	90	
Turbine 5	900	400	120	120	
Turbine 6	100	700	120	120	
Turbine 7	300	700	120	90	
Turbine 8	500	700	120	60	
Turbine 9	700	700	120	30	
Turbine 10	900	700	120	0	
Airplane	1000	1000	300		50

Figure 7: Locations of emitters

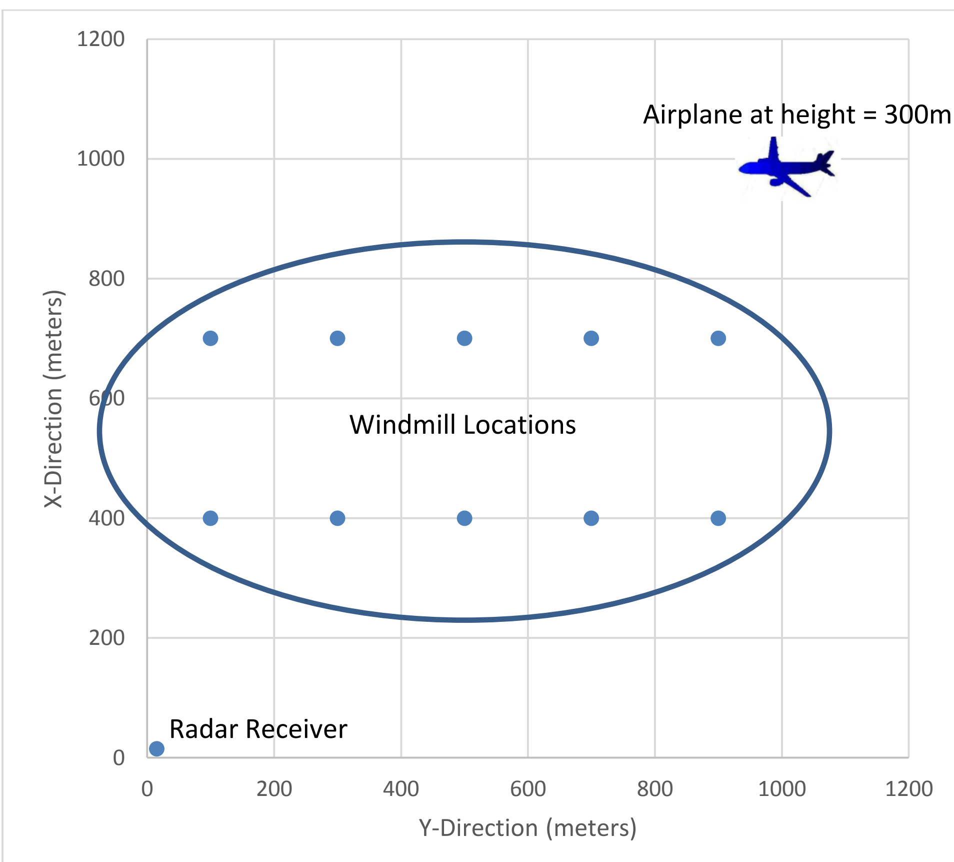

Figure 8: Location of wind turbines and aircraft on xy plane at height, z = 0

The computation is performed with and without aircraft. The combined signal due to multiple arrivals is shown in Figure 9 and it can be seen that the computed signal compares well with the exact signal.

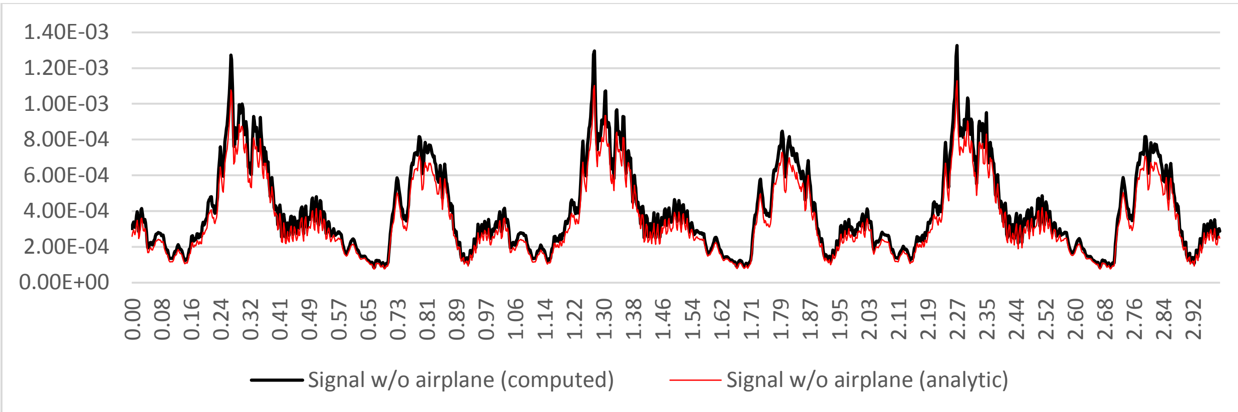

Figure 9: 10 Windmill Farm Radar Envelope over 1 Windmill Period

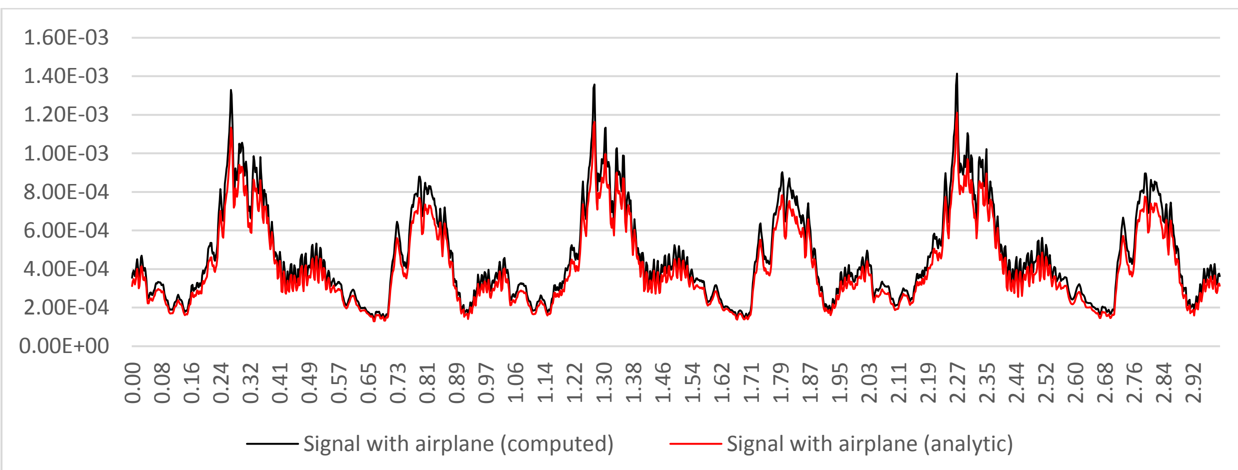

Figure 10:10 Windmill Farm Radar Envelope over 1 Windmill Period, with Airplane

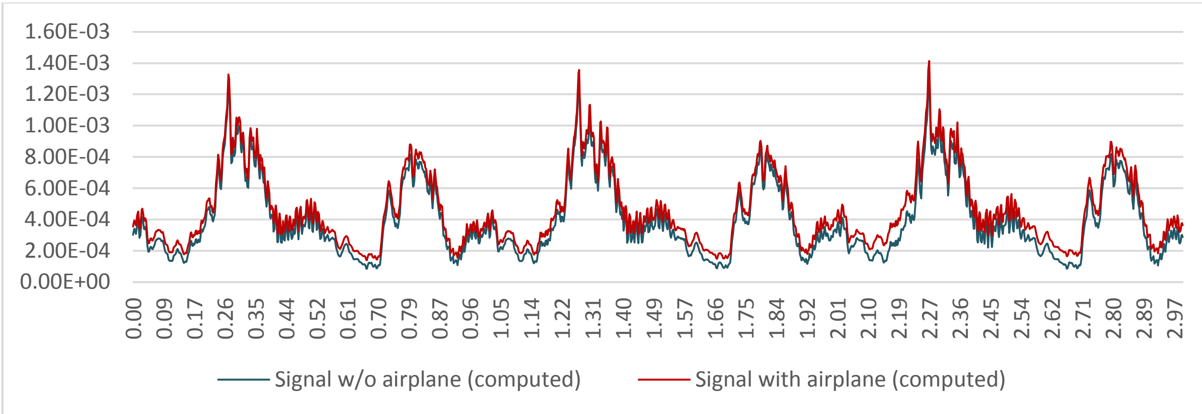

Figure 11: Wind farm Envelope with and without Airplane